

Comparison of Aircraft Trajectory Predictor Capabilities and Their Impacts on Air Traffic Management Automation Interoperability

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Advanced air traffic management concepts in both the U.S. and Europe are proposing increased sharing of trajectory information between automation systems to improve interoperability and ultimately achieve capacity benefits. Since this automation, especially those that provide real-time decision support, rely on aircraft trajectory prediction to enable their functionality, the success of this interoperability is directly dependent on the ability of the trajectory predictors within these systems to either use or be replaced by the shared trajectory information. This paper presents a comparison of the capabilities of five different trajectory predictors supporting automation covering a range of domains (airborne, ground-based) and environments (research, operational). The comparison results illustrate the similarities and differences between these trajectory predictors in the constraints handled, internal modeling, and output trajectory data. To illustrate the impacts of these capability similarities and differences on interoperability, an air-ground data sharing example using three of the analyzed trajectory predictors is presented. The example uses an environment where airborne flight management systems send trajectory information via datalink to two ground-based systems supporting controller conflict detection and resolution to explore three different types of trajectory data sharing: intent, behavior model, and 4D trajectory. The example scenario demonstrates that achieving interoperability through trajectory data sharing requires an understanding of the trajectory prediction assumptions and requirements for both the sending and receiving systems.

Nomenclature

<i>AP16</i>	=	FAA/Eurocontrol Action Plan 16 on common trajectory prediction
<i>APM</i>	=	aircraft performance model
<i>BADA</i>	=	Base of Aircraft Data (Standard Aircraft Performance Model)
<i>CAS</i>	=	calibrated airspeed
<i>CTAS</i>	=	Center/TRACON Automation System
<i>CTAS ER</i>	=	CTAS en route TP
<i>CTAS TA</i>	=	CTAS terminal area TP
<i>DME</i>	=	Distance Measuring Equipment
<i>ERAM</i>	=	En Route Automation Modernization
<i>ERAM r1</i>	=	ERAM release 1
<i>FACET</i>	=	Future Air Traffic Management Concepts Evaluation Tool
<i>FMS</i>	=	flight management system
<i>FPA</i>	=	flight path angle
<i>GE</i>	=	General Electric

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<i>IAS</i>	=	indicated airspeed
<i>ITWS</i>	=	Integrated Terminal Weather System
<i>LNAV</i>	=	lateral navigation guidance
<i>TAS</i>	=	true airspeed
<i>TBO</i>	=	trajectory-based operations
<i>TOD</i>	=	top of descent
<i>TP</i>	=	trajectory predictor
<i>VNAV</i>	=	vertical navigation guidance

I. Introduction

TO enable advanced air traffic management concepts, such as trajectory-based operations, the NextGen concept in the U.S. is increasing the amount of data shared between automation in the National Airspace System.¹ Trajectory-Based Operations utilize predicted aircraft four-dimensional trajectories to “assess the effects of proposed trajectories and resource allocation plans, allowing both service providers and operators to understand the implications of demand and identify where constraints need further mitigation.” Understanding the functional and performance differences between disparate trajectory predictors (TPs) is critical for enabling the interoperability between these systems. If trajectory and aircraft intent data are to be effectively shared, the variation in requirements must be properly understood. This understanding is necessary to determine the minimum data that must be shared to achieve interoperability without degrading performance.

Over the past decade, several US and European efforts to understand the differences between disparate trajectory predictors met with little success. These efforts attempted to survey and document the current and future DST requirements for trajectory prediction capabilities to identify commonalities and differences. The content varied widely from one organization to another, the material was inconsistent in what was documented (little comparable overlap), and the scope of information was significantly incomplete. The wide range of approaches taken to implement TPs made it difficult to understand the similarities (and true differences) the requirements.

A team of companies with expertise in TP technology (Lockheed-Martin, L-3 Communications, and GE-Aviation) documented the capabilities of five TPs from different domains, environments and functional support^{2,3,4,5}. The five TPs were chosen to cover a range of current day TP applications, including air- and ground-based support of control, traffic flow management and flight planning systems in both research lab and operational deployment environments. These documents all followed a common document structure, referred to as the Requirements Framework, which was developed by NASA, Lockheed Martin and L-3 Communications to enable a clear, consistent, complete and cross-comparable documentation of TP requirements and capabilities. This common format allowed a formal comparison of the TPs to be conducted.

The paper begins by describing the five TPs that were the focus of the TP comparison and by the approaches taken to perform the comparison. Next, detailed descriptions of the results of the TP comparison are presented. Finally, an interoperability scenario is described where airborne FMS data is sent via datalink to ground-based systems performing conflict detection and resolution functions. Using the comparison results as a foundation, this scenario illustrates the challenges disparate TP capabilities can provide in trying to achieve system interoperability.

II. Trajectory Prediction Comparison

In support of the FAA/Eurocontrol Research & Development Committee (Action Plan 16) on Common Trajectory Prediction, NASA has been studying state-of-the-art trajectory predictor (TP) technologies in an attempt to better understand commonalities and differences in TP capabilities and requirements. Under this project, the capabilities of four state of the art TP technologies were captured, documented and compared:

1. NASA’s Center/TRACON Automation System (CTAS) En Route TP²
2. NASA’s CTAS Terminal Area TP³
3. NASA’s Future Air Traffic Management Concepts Evaluation Tool (FACET) TP⁴
4. GE Aviation Flight Management System (FMS) TP⁵

These four documents all follow a common capabilities framework that leveraged the latest version of the AP16 Common TP structure to enable effective cross-comparison of the documented capabilities. During the development of these documents, a minimal level of cross-comparison was also performed to identify documentation techniques

that could further enhance effective capability comparisons. The primary results of these early comparisons were modifications to the documentation approach (e.g., the use of abstraction and the use of standardized tables in capturing certain capabilities) to further enhance the cross-comparability of the documents.

Under a separate Space Act Agreement with NASA, the capabilities of a fifth TP technology were captured by Lockheed Martin and added to the comparison:

5. Release 1 of the FAA's En Route Automation Modernization (ERAM) TP ⁶

This document was not a part of the early comparison effort, but did follow a similar document framework (based on an earlier revision of the AP16 Common TP structure) to the other four documents.

In developing an approach to compare the five TP technologies, it was desired to achieve two main goals:

1. Compare specific capabilities that are currently known to illustrate similarities or differences of interest between the TPs
2. Compare all capabilities in a systematic way in an attempt to identify new, currently unknown similarities or differences of interest between the TPs

The first goal was relatively easy to meet after the capabilities of known interest were identified. The second goal was much more difficult to achieve.

To meet both goals, two separate comparison approaches were developed and performed. The first goal was met by identifying a series of capabilities of interest to the organizations involved in this project (termed "orthogonal looks" by NASA) and directly comparing them. These comparisons were performed verbally during a face-to-face meeting between representative experts for each TP at the Engility facility in Billerica, MA and through follow-up emails. The second goal was met by generating a comparison matrix of major capabilities from the TP capability documents. This comparison matrix focused on "top-level" capabilities, i.e., those that define the range of situations handled by the TP rather than details on how those situations are handled. Both approaches are described in more detail next.

A. Orthogonal Looks Comparison Approach

The orthogonal look approach was designed to compare TP capabilities of specific interest to the organizations involved in the project. The organizations were NASA (CTAS and FACET TPs), Lockheed Martin (ERAM TP) and GE Aviation (FMS TP).[§] All three organizations were requested to provide specific questions (orthogonal looks) they would like answered by each of TP capabilities. Both NASA and Lockheed Martin submitted a list. GE Aviation had a single question that was equivalent to a Lockheed Martin question. Both lists of orthogonal looks were answered and discussed in a face-to-face meeting at the Engility facility in Billerica, MA on March 25, 2009. TP experts from each organization were present and the majority of questions were discussed directly during the meeting. Questions that were either not covered during the meeting (due to time limitations) or which required additional investigation by one or more TP experts to answer properly were covered through follow-up emails.

B. Top-Level Capability Comparison Approach

Defining an approach to identify new, currently unknown similarities and differences between the five TP technologies presented some challenges. The simplest approach would have been to compare the five capabilities documents, section by section. To perform such a comparison was the original objective of using a common framework based on the AP16 Common TP structure. Unfortunately, using this type of comparison approach at this stage of the framework's development posed some potentially significant issues:

It relied on every document using the exact same framework sections: This was not the case since the ERAM document used an earlier version of the framework than the version used by the other documents. Even in the case of the four TP documents that followed the same framework version, the effectiveness of the framework to support such a comparison was still unknown. It was desired to have an approach that was robust to potential issues with the framework, while providing potential insight into how to improve the framework to support such a section-by-section comparison.

[§] Engility Corporation is not the owner of a particular TP product and was responsible for the ultimate comparison results and, as such, did not provide specific comparisons of interest.

It relied on every TP expert filling out the framework sections in the same way: The AP16 common TP structure (the foundation of the framework) is an effective tool in describing a wide range of TPs, but it takes skill to map the capabilities of a specific TP to the AP16 Common TP structure. Since the AP16 Common TP structure is still being developed and is not yet widely familiar to the general TP community, it is not surprising that different TP experts interpret it differently and that this could lead to comparable capabilities being captured in different sections of the capabilities documents.

Identified during the early comparisons of four of the TP technologies, the boundary between the TP and its client application chosen by the documenting TP expert impacts where in the framework capabilities were captured. Every TP expert had to decide what capabilities to include within the TP and which to consider part of the client application.** This decision not only impacted where, but whether certain capabilities would be captured in the document. Different decisions by the TP experts could impact a section-by-section analysis.

It did not provide any approach to scoping the comparisons: The framework was designed to capture the capabilities of a TP to a very detailed level. Decisions about how much detail to provide were left to the TP experts, but all five documents captured very detailed information about their TP's processing. It was not clear to what level an initial search for new interesting comparisons should be performed and a section-by-section comparison did not help to answer this question. Actually, it was feared that covering all sections would tend to lead to many comparisons at the lowest level (where differences are expected), potentially leading to a failure to identify the most significant similarities/differences at a higher level (i.e., hard to see the forest through the trees).

An alternative approach was developed to:

1. try and identify the most significant capability similarities/differences while giving insight into potential additional comparisons that could be performed later
2. be robust to potential limitations in the current framework with the idea that the comparison results would feed back into framework improvements

The approach compared the “top-level” capabilities for each TP, focusing on available types of input data, output data, math models, and major behaviors that could be predicted without getting into details on how the TP actually developed a trajectory. Seven sets of data were captured for each TP in an excel spreadsheet (called the comparison matrix):

- Input state data
- Constraints handled
- Behavior models used
- Math models used
- Input atmospheric models
- Update processing supported
- Output trajectory data

Each TP capability document was read from beginning to end and any reference to a capability falling under one of the seven data sets was captured. This eliminated the chance that comparable capabilities captured in different framework sections would be missed. Four out of the five documents were all read by the same TP expert and the data entered into the comparison matrix (the FACET document being the only exception; this data was entered by a NASA TP expert). The final comparison matrix was reviewed by all of the TP experts to check for correctness.

The entire comparison matrix was also reviewed at the face-to-face meeting at the Engility facility in Billerica, MA on March 24-25, 2009. TP experts from each organization were present and the matrix was updated with corrections, as necessary.

** This decision would appear to be a simple one, but in practice is quite complex. See reference 7 for details.

III. TP Comparison Results

The complete set of comparison results, for both the orthogonal look and the top-level capability comparisons, are provided in reference 8. Below is a subset of some of the results for the top-level capability comparisons. This data will be pared down in the final paper to just the most relevant results.

A. Input State Data

Input state data supports several capabilities in the TP, including:

- Defining the initial condition of the trajectory
- Identifying the initial lateral and vertical maneuvers
- Identifying missing intent data (e.g., when input state is not on the aircraft's flight plan route)

Differences in the input state data available to different TPs reflects differences in the environments in which these TPs operate. It also illustrates differences in data available for determining initial maneuvers and intent modeling.

Table 1 provides the lateral input state data for the five TPs. All five TPs receive position and true course data. The two CTAS TPs receive position in the local X/Y coordinate frame used by the Host computer, where the rest receive position in latitude and longitude. The use of a local Cartesian coordinate frame by CTAS reflects the limited airspace supported by each instance of this system (i.e., one Air Route Traffic Control Center (ARTCC)). True course data is available to all of the ground-based TPs, but since it is generated by processing previous radar tracks, it is susceptible to certain types of errors. The GE FMS TP has access to both true course and magnetic heading from the onboard avionics. Both the GE FMS and ERAM TPs receive indicators of whether the initial state is in a turn. The GE FMS TP receives the current roll angle from the onboard avionics, where the ERAM TP receives an "In Turn" indication from ERAM.^{††} Knowledge of the actual roll angle provides the most information about an aircraft that is currently in a turn.

Table 1: State data: lateral

TP	Position		True Course	Magnetic Heading	Attitude	
	X/Y	Lat/Lon			Roll Angle	In Turn?
CTAS ER	•		•			
CTAS TA	•		•			
FACET		•	•			
GE FMS		•	•	•	•	
ERAM r1		•	•			•

Table 3 shows the input time, altitude and speed data for the five TPs. All five TPs receive both time and corrected altitude (corrected for altimeter setting). The ERAM TP also receives an established altitude which is the last Mode C or pilot-reported altitude from the aircraft. All five TPs also receive ground speed, which is the main form of speed available from ground sensors (e.g., radar tracks). The CTAS TPs can also accept a true airspeed (TAS) input, which is used primarily for non-active aircraft (i.e., using flight plan information, including the filed speed, which is a true airspeed, when no track data has been received). The GE FMS TP receives the full suite of speeds, including Mach, calibrated airspeed (CAS), TAS, and ground speed, all of which are available from the onboard avionics. All but the FACET TP also receive the current vertical speed of the aircraft.

Table 5 shows a range of other input data related to the state of the aircraft. All TPs are aware of the aircraft type (e.g., Boeing 757-200). Weight is received by the CTAS En Route and the GE FMS TP, though the CTAS value is typically down-linked from the aircraft where the GE FMS TP receives weight from an onboard weight determination system. The GE FMS TP receives extensive information on the engines and aircraft configuration. The ERAM TP receives the equipment onboard the aircraft as well as whether the state data was generated by "coasting" previous track information. The GE FMS TP also knows the aircraft's navigation equipment.

^{††} ERAM evaluates past radar tracks to determine whether the current track should be considered in a turn.

Table 3: State data: time, altitude and speed

TP	Time	Altitude		Speed				Vertical Speed
		Corrected	Established	Mach	CAS	TAS	Ground	
CTAS ER	•	•				•	•	•
CTAS TA	•	•				•	•	•
FACET	•	•					•	
GE FMS	•	•		•	•	•	•	•
ERAM r1	•	•	•				•	•

Table 5: State data: other

TP	Aircraft Type	Weight	Additional Engine & Configuration Data	Navigation Equipage	Coast Indicator
CTAS ER	•	•			
CTAS TA	•				
FACET	•				
GE FMS	•	•	•*	•	
ERAM r1	•			•	•

* Engine Bleed (air-conditioning and anti-ice), Engine State (Engines Off, All Engines On, Engine Out), Configuration information (slats position and flap position), and Weight On Wheels indication.

B. Constraints Handled

A TP generates a trajectory to achieve, if possible, the input constraints on the aircraft. These constraints may be explicitly defined as input intent data (e.g., a clearance to maintain a given heading), may be derived directly from input intent data (e.g., an input flight plan route is decomposed into a series of turn waypoints through route parsing), or may be added by the TP through intent modeling to create a sufficient set for integration (e.g., adding a waypoint capture constraint to connect the aircraft initial condition to an input route). Comparing the set of constraints that a TP is able to achieve provides insight into the scope of trajectory problems that the TP can predict.

1. Lateral Constraints

Table 7 shows the waypoint-defined lateral constraints that each of the five TP's can accommodate. Each TP is able to end the trajectory at a specified waypoint. Though trajectory end conditions will be discussed in more detail later, this does indicate that all of the TPs have a similar approach to ending the trajectory (e.g., none of them require ending the trajectory at a fixed look-ahead time). Each TP can also handle waypoint-defined turns, such as those found in typical flight plan routes (e.g., inside turns). This was expected since all of the TPs are using some form of FAA flight plan route definitions.

Table 7: Lateral constraints: waypoint-defined

TP	Trajectory End	Turn	Constant Radius Arc	DME Arc From Fix	Hold	Procedure Turn
CTAS ER	•	•			*	
CTAS TA	•	•				
FACET	•	•				
GE FMS	•	•	•	•	•	•
ERAM r1	•	•			*	

* CTAS and ERAM handle Hold clearances, but do not build the race track.

The GE FMS does handle some additional waypoint-defined constraints that are specific to its environment.^{††} For example, the “DME Arc From Fix” constraint is used in very specific (and infrequent) terminal procedures.

^{††} The GE FMS is able to handle all of the waypoint-based constraints defined in the ARINC 424 standard. The different types of 424 leg constraints are specific to the way the onboard guidance and navigation systems will interact to laterally control the aircraft. The ARINC 424 constraints were evaluated and generalized for comparison

Similarly, the “Procedure Turn” is used by the FMS to perform a very specific direction reversal maneuver. Handling of these additional constraints is not required by the environments of the other four TPs.

The handling of a “Hold” constraint is a very interesting example of the difference in requirements placed on a TP by different client applications. Three of the client applications (CTAS, ERAM, and GE FMS) handle Hold constraints. Only one (the GE FMS) uses the TP to build the actual “race track” path of the aircraft within the Hold and the transition to the racetrack from the previous route leg. Since the GE FMS TP is supporting the aircraft guidance function during a Hold maneuver, it makes sense that it would have this type of requirement. Neither the CTAS ER nor the ERAM TP builds the race track path, but both do handle the effects of Hold constraints within the client application. For example, CTAS protects the airspace around the Hold constraint during conflict detection and ERAM does not conflict probe downstream of a Hold constraint.

Table 9 shows the route/radial-defined lateral constraints that each of the five TP’s can accommodate. Each TP can handle routes defined by great circle path route segments. Similar to the waypoint-defined turn constraints, this was expected since these are the typical route segment definitions found in FAA flight plans. Three of the TPs (all except the CTAS Terminal Area and FACET TPs) can handle waypoint capture constraints to transition to a route. A waypoint capture constraint indicates that the aircraft should immediately turn and proceed directly to the identified waypoint and then follow the route after that waypoint. Again, this is a typical FAA routing approach, as well as a common intent modeling method for connecting an off-route initial condition to a route, so it is not surprising that most of the TPs support this constraint. The CTAS Terminal Area TP does not have a flight plan route in the terminal area to connect to, so this capability isn’t applicable. The FACET TP does not include this capability because its TP is limited to predicting aircraft following their routes.^{§§} The CTAS En Route TP can accept an additional capture delay time constraint with a waypoint capture constraint. This constraint defines how long (in time) the aircraft should travel before turning to capture the identified capture waypoint. CTAS uses this to develop lateral delay absorption advisories.

Table 9: Lateral constraints: route/radial-defined

TP	Great Circle Path	Waypoint Capture	Capture Delay Time	Intercept DME Distance	Intercept Route Leg	Intercept Radial	Lateral Offset
CTAS ER	•	•	•				
CTAS TA	•						
FACET	•						
GE FMS	•	•		•	•	•	•
ERAM r1	•	•			•		

Both the GE FMS and ERAM TP can accommodate an intercept route leg constraint. This constraint indicates that the aircraft should transition to the input route when the current path of the aircraft intersects the input route. The GE FMS also has the ability to handle two other intercepts: intercept DME distance and intercept radial. These constraints appear to be only required for the GE FMS TP’s environment.

The GE FMS TP can also accept a lateral offset constraint. This constraint defines the start, end, and required dimensions (e.g., displacement of the offset from the input route) to create an offset path that is laterally displaced from the input route. This type of offset path could also have been generated outside of the TP and sent in as a new route using other constraints previously discussed. The use of a lateral offset constraint by the GE FMS TP appears to support the specific operational environment of the FMS, where it is desired to maintain knowledge of the original route while predicting the offset path.

2. Vertical Constraints

Table 6 shows the speed constraints that each of the TPs can accommodate. All five TPs can accommodate some type of cruise speed constraint, whether the constraint be in Mach, CAS, or TAS (the specific speed types accepted are based on the environment of the TP). Since most aircraft spend the majority of their flight in level cruise, it is to be expected that all of the TPs would handle speed constraints in cruise. All but the CTAS Terminal Area TP also handle speed constraints in Climb and Descent. The CTAS En Route, FACET, and GE FMS TPs all directly handle

with the other TP constraint handling. Only a few (Constant Radius Arc, DME Arc From Fix, etc.) were considered different enough from the other constraints to warrant explicit identification in these tables.

^{§§} The capabilities of the entire FACET system are not limited to just these cases, but it only uses its TP for cases where the aircraft is on its route. For more information, see reference 4.

a climb or descent speed profile (Mach and CAS) constraint. ERAM uses an empirically derived performance model, which defines TAS as a function of altitude for each aircraft type. This TAS schedule is based on observations of actual aircraft performance, which means it is indirectly modeling a range of climb and descent speed profiles. The CTAS Terminal Area TP and GE FMS TP both accommodate an approach speed since they develop trajectories for the terminal area. The GE FMS TP also handles speed constraints for Hold, Takeoff, and Engine Out scenarios.

Table 6: Vertical constraints: speeds

TP	Cruise Speed	Descent Speed	Climb Speed	Approach	Hold	Takeoff	Engine Out Speed
CTAS ER	Mach, CAS, TAS	Mach, CAS	Mach, CAS				
CTAS TA	CAS*			•			
FACET	Mach, CAS, TAS	Mach, CAS	Mach, CAS				
GE FMS	Mach, CAS	Mach, CAS	Mach, CAS	•	•	•	•
ERAM r1	Mach, TAS	Empirical	Empirical				

* In terminal area, the speed constraint impacts both level flight and descending path segments.

The differences in handling climb and descent speeds, especially between the CTAS, GE FMS and ERAM TPs, illustrate the differences in TP requirements from their client systems. The CTAS En Route TP supports a range of client applications (e.g., CTAS decision support tools). One of them is the En Route Descent Advisor, which develops descent speed profile (Mach and CAS) clearance advisories for conflict-free schedule-conformant aircraft trajectories. In this environment, the TP is used to predict the impact of a specific descent Mach and CAS profile, hence the TP's ability to directly use descent Mach and CAS as constraints. When the CTAS En Route TP is used in environments where the Descent Speed profile is not known (e.g., in support of the Traffic Management Advisor), it uses default speed values based on company procedures for the aircraft type. This enables the TP to support both environments. On the other hand, the ERAM TP does not need to support the advisory generation environment of the CTAS En Route TP. Its approach of using an empirically-based model of aircraft speed (and vertical rate) has been developed to be effective when the actual speed profile is not known. For the GE FMS TP, the aircraft is always aware of its own Mach and CAS, so it obviously uses this information to its advantage.

Table 7 and Table 8 show the non-waypoint-defined and waypoint-defined altitude constraints, respectively, that each of the TPs can accommodate. The FACET TP can only handle a cruise altitude constraint. This is consistent with its lower fidelity approach to trajectory modeling. For non-waypoint defined altitude constraints, the CTAS En Route, GE FMS and ERAM TPs all handle cruise altitude, interim altitude and departure/arrival speed limit altitude constraints (e.g., 250kt speed limit at 10,000 ft), which is not unexpected since these are common altitude constraints in today's operations. Both the CTAS TPs and GE FMS TP handle a defined altitude at which to apply an externally entered altimeter setting, though ERAM does not. The GE FMS TP also handles an Optimal Step Altitude (defines a target change in cruise altitude) and two altitude constraints related to takeoff (Acceleration Altitude and Thrust Reduction Altitude). The CTAS Terminal Area TP deals with an altitude "constraint" that defines the top of the TRACON airspace, which it uses to separate en route pilot behavior from TRACON behavior.***

*** The CTAS terminal Area TP receives initial radar tracks when the aircraft is still in en route airspace. The Max TRACON Altitude constraint defines at what altitude the aircraft enters the terminal area.

Table 7: Vertical constraints: altitudes

TP	Cruise Alt	Interim Alt	Departure/Arrival Speed Limit Alt	Max TRACON Alt	Optimal Step Alt	Transition Alt (altimeter setting)	Accel (V2 to Climb)	Thrust Reduction
CTAS ER	•	•	•			•		
CTAS TA				•		•		
FACET	•							
GE FMS	•	•	•		•	•	•	•
ERAM r1	•	•	•					

For waypoint-defined altitude constraints, the GE FMS and ERAM TPs handle the most types, which is consistent with their deployment-level operational focus. All TPs (except the FACET TP) can handle AT constraints. The two CTAS TPs don't handle AT or Below constraints, which is consistent with their historical emphasis on arrival traffic handling. The GE FMS TP does not handle Remain AT constraints, which is consistent with the fact that these are very, very rare (added for a very specific operational situation). Both the GE FMS and ERAM can handle window constraints, which are just a combination of an AT or ABOVE and an AT or BELOW constraint at the same waypoint. It should be noted that window constraints are not allowed within RNAV procedures because not all FMS can handle them.

Table 8: Vertical constraints: waypoint-defined altitude

TP	AT	AT or ABOVE	AT or BELOW	Window	Remain AT	Change AT
CTAS ER	•					
CTAS TA	•	•				
FACET						
GE FMS	•	•	•	•		•
ERAM r1	•	•	•	•	•	•

Table 9 shows a range of other waypoint-defined constraints that the TPs can accommodate. All of the TPs (except the FACET TP) can handle both Start AT and End AT speed constraints, though only ERAM handles Mach versions of these constraints. Both the CTAS En Route and GE FMS TPs can handle time constraints, which is not surprising since meet-time (required time-of-arrival) functionality has been a part of these systems for decades. The ERAM TP can handle a delay constraint added at a waypoint. ERAM uses this delay constraint to handle delays filed in a route (e.g., a military aircraft could be off performing a refueling operation or practicing a bombing run). The GE FMS TP also handles a waypoint-define (start and end) temporary change to a new Mach speed and a flight path angle constraint; both constraints are unique to the FMS environment.

Table 9: Vertical constraints: waypoint-defined speed, time & other

TP	Speed (AT or BELOW)			Initiate/End Mach	Time	Delay	Flight Path Angle
	Mach	IAS/CAS	Start AT & End AT				
CTAS ER		•	•		•		
CTAS TA		•	•				
FACET							
GE FMS		•	•	•	•		•
ERAM r1	•	•	•			•	

C. Behavior Models Used

Behavior models define the maneuvers predicted by a TP. They are typically defined in layers, with more general maneuvers (e.g., climb) being broken up into more specific maneuver components (e.g., constant CAS climb at max climb thrust followed by a constant Mach climb at max climb thrust). Comparing the different behavior

models used by the different TPs highlights similarities and differences in which maneuvers are predicted and to what level of detail are they predicted.

1. Lateral Behavior Models

Table 10 shows the different behavior models used by the TPs to define the aircraft's maneuvers when following the straight (i.e., non-turning) portion of a route. All five of the TPs model some form of following a great circle path (newer GE FMS TPs use WGS84 paths). The FACET TP is an interesting case in that it is unable to follow the great circle path defined by two waypoints (the typical flight plan route case). It is only able to model following a great circle path from the current position to a waypoint, which is only equivalent to the two waypoint case when the aircraft is initially on the path defined by two waypoints. The GE FMS TP also has the ability to model following a constant course or heading to a waypoint or some other termination point.

Table 10: Route-following behavior models: straight

TP	Great Circle			Constant Course		Constant Heading
	WP to WP	To a WP	To Other*	To a WP	To Other*	To Other*
CTAS ER	•					
CTAS TA	•					
FACET		•				
GE FMS	•	•	•	•	•	•
ERAM r1	•					

* The GE FMS can follow a great circle path, constant course or constant heading to a variety of termination points, including a specified distance, DME distance, an altitude, a radial or manual termination point.

Table 11 shows the different behavior models used by the TPs for performing turns associated with following a route. All of the TPs are able to model immediate turns to capture the next waypoint in the route (e.g., used when the initial condition is in a turn or the current track is not along the route direction) and model the aircraft performing an “inside” (i.e., non-fly over) turn. These are both typical behavior model maneuvers associated with flying a flight plan route. The CTAS TPs and the GE FMS TP also have the ability to model a turn overshoot maneuver, used by aircraft for extreme (typically greater than 135 degree) inside turns. ERAM doesn't require such a behavior model since its math model uses instantaneous turn modeling (see Math Models below), which would not show any difference between an overshoot and a non-overshoot turn. The CTAS TPs and the GE FMS TP also model two types of fly-over waypoint turns: one that Begins AT the turn waypoint and the other that Ends AT the turn waypoint. Again, the ERAM TP's choice for turn modeling would make such a distinction irrelevant. Also, though possible in en route airspace, these are more typical in modeling terminal airspace maneuvers. This may be the main reason that FACET does not model these types of turns. The GE FMS TP also performs two additional, specialized turn types: constant radius and DME arc turns.

Table 11: Route-following behavior models: turns

TP	Turn to Capture WP	Inside Turn		Begin AT WP	End AT WP	Constant Radius Arc	DME Arc
		Normal	Overshoot				
CTAS ER	•	•	•	•	•		
CTAS TA	•	•	•	•	•		
FACET	•	•					
GE FMS	•	•	•	•	•	•	•
ERAM r1	•	•					

Table 12 shows the behavior models used for capturing a route. The CTAS Terminal Area and FACET TPs do not support capturing a route because their initial conditions are never off of their routes (see earlier discussion). The CTAS En Route, GE FMS and ERAM TPs all support waypoint capture behaviors, including a modeled delay before initiating the turn to the capture waypoint, the turn, and a great circle path to the capture waypoint. Only the GE FMS TP supports route intercept maneuvers, including both constant heading and constant course intercepts, to accommodate its input intercept constraints (see Table 9). It should be noted that the ERAM TP does handle

intercept route leg constraints, but the intercept point is geometrically calculated and converted into a turn waypoint constraint, so no intercept behavior model is required. Only the CTAS En Route TP supports the Path Stretch behavior model to accommodate its Capture Delay Time input constraint (see Table 9).

Table 12: Route capturing behavioral models

TP	Waypoint Capture			Route Intercept			Path Stretch	
	Delay Before Capture*	Turn to Capture WP	Great Circle to WP	Delay Before Intercept	Constant Course Intercept	Constant Heading Intercept	Turn to Capture Heading	Delay Before Capture
CTAS ER	•	•	•				•	•
CTAS TA								
FACET								
GE FMS	•	•	•	•	•	•		
ERAM r1	•	•	•					

* This delay models lag time in pilot action, not an externally entered delay constraint (that is handled by the Path Stretch behavior model).

2. Vertical Behavior Models

Table 13 shows the behavior models used to model an aircraft during a climb maneuver. The CTAS Terminal Area TP does not support climb trajectories, since it is focused on arrival traffic. All of the other TPs model the climbing capture of a desired climb speed. For the CTAS En Route and GE FMS TPs, the speed captured can be either a target Mach or CAS. For the FACET and ERAM TPs, the speed constraints in climb are a performance model defined TAS schedule (see earlier for a discussion of ERAM's empirically-based TAS schedule), so the speed captured is always a TAS. For the majority of the climb, the CTAS En Route and GE FMS TPs can use either a constant speed (Mach or CAS) and known throttle setting (e.g., max climb thrust) or a constant speed and a constant vertical rate. The FACET and ERAM TPs do not define the behavior model in any more detail than as a climb. Both rely on their math model representation for accuracy. Additionally, the GE FMS and ERAM TPs have the ability to model level off behavior in the climb maneuver, both in capturing a desired speed and maintaining that speed at the constant altitude. The GE FMS TP also has the ability to model takeoff behavior, using two behavior models (ground roll acceleration and constant CAS takeoff) for this purpose.

Table 13: Climb behavior models

TP	Climbing						Level	
	Ground Roll Accel	Constant CAS Takeoff	Capture Climb Speed*	Climb	Constant Speed, Thrust Setting	Constant Speed, Vertical Speed	Capture Speed	Constant Speed
CTAS ER			CAS, Mach		CAS, Mach	CAS, Mach		
CTAS TA								
FACET			TAS**	•				
GE FMS	•	•	CAS, Mach		CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach
ERAM r1			TAS***	•			TAS	TAS

* Includes both End AT and Begin AT speed captures. FACET is only TP that can only do Begin AT.

** FACET uses a performance model derived TAS schedule.

*** ERAM uses an empirically derived TAS schedule, modified (in the case of its Aircraft Trajectory only) by a factor based on observed speed.

Table 14 shows the behavior models supported for aircraft in their cruise phase of flight. All of the TPs support constant speed cruise segments, as well as level flight transitions to a new cruise speed. The remaining two behavior models are to support changes in the cruise altitude. Neither the CTAS Terminal Area nor the FACET TP support changes in cruise altitude. For step descents to a new cruise altitude, both the CTAS En Route and GE FMS TPs can do either constant speed (Mach or CAS) and known thrust setting (e.g., idle thrust) or constant speed and constant

vertical speed maneuvers. The ERAM TP does not define the maneuver in any more detail than as a descent (again relying on its empirical aircraft performance model for accuracy). The GE FMS and ERAM TPs have the added ability to model a speed change during the step descent. The situation is similar for step climbs, except that the CTAS En Route and GE FMS TPs only use a constant speed, known throttle setting (e.g., max climb thrust) model for these maneuvers.

Table 14: Cruise behavioral models

TP	Level		Altitude Step: Descent				Altitude Step: Climb		
	Constant Speed	Capture Speed*	Capture Speed	Descent	Constant Speed, Thrust**	Constant Speed, Vertical Speed	Capture Speed	Climb	Constant Speed, Thrust Setting
CTAS ER	•	•			CAS, Mach	CAS, Mach			CAS, Mach
CTAS TA	•	•							
FACET	•	•							
GE FMS	•	•	•		CAS, Mach	CAS, Mach	•		CAS, Mach
ERAM r1	•	•	•	•			•	•	

* Includes Begin AT and End AT as well as acceleration and deceleration.

** Both CTAS and the FMS could do Idle Thrust step descents, but currently do constant vertical speed.

Table 15 shows the behavior models supported for aircraft in their descent phase of flight. For the descending maneuvers, each TP has its own behavioral modeling approach. The GE FMS TP has the most extensive approach, using idle thrust, constant vertical speed, and constant flight path angle versions of capturing a speed and holding a speed (Mach or CAS) constant. The CTAS En Route TP uses the same idle thrust and constant flight path angle versions of holding a speed (Mach or CAS) constant, but performs a non-specific (relies on the mathematic model) descending capture of a speed. Due to its low altitude trajectories, the CTAS Terminal Area only does constant flight path angle versions of capturing and maintaining a speed (CAS only at these altitudes). Both the FACET and ERAM TPs use the same type of model as described above for their climb behavior models. All but the FACET TP can also handle a level off segment during a descent. The CTAS En Route and GE FMS TPs can handle both capturing and maintaining a target Mach or CAS. The CTAS Terminal Area TP can capture and maintain a CAS. The ERAM TP can capture and maintain the TAS from its empirical model.

Table 15: Descent behavioral models

TP	Descending								Level	
	Descent	Capture Speed				Constant Speed				
		Descent	Idle Thrust	Vertical Speed	Flight Path Angle	Idle Thrust	Vertical Speed	Flight Path Angle	Capture Speed	Constant Speed
CTAS ER		CAS, Mach				CAS, Mach		CAS, Mach	CAS, Mach*	CAS, Mach
CTAS TA					CAS			CAS	CAS	CAS
FACET	•	TAS								
GE FMS			CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach	CAS, Mach
ERAM r1	•	TAS***							TAS	TAS

* CTAS does not decelerate to Mach, though it has the capability.

** FACET uses a performance model derived TAS schedule.

*** ERAM uses an empirically derived TAS schedule, modified (in the case of its Aircraft Trajectory only) by a factor based on observed speed.

D. Math Models Used

Behavioral models are mapped to mathematical models within the TP to define either a set of equations of motion to integrate or a geometric algorithm to predict the aircraft trajectory. Comparing TP math modeling

approaches gives insight into the accuracy achievable by the TP. First, the general integration approaches between the TPs are compared. Next, the specific lateral and vertical math models used by the TPs are compared.

1. General Integration Approach

Table 16 summarizes the general integration approaches used by each of the five TPs. Only the FACET TP integrates equations of motion for the lateral path of the trajectory. Each of the other TPs geometrically approximates the lateral path of the aircraft prior to integrating the vertical profile. In all cases but ERAM, these TPs create an approximation of the vertical profile to calculate required turn model parameters (e.g., turn radius and center).^{†††} The FACET TP performs a “fast time simulation” to create its trajectory and its integration of both lateral and vertical equations of motion only in a forward direction is consistent with this design. For the vertical approach, the CTAS En Route and GE FMS TPs perform both forward and backward integration (depending on the specific math model) of the vertical (both altitude and longitudinal) equations of motion. The CTAS Terminal Area TP only integrates longitudinal equations of motion; the altitude path is geometrically calculated from the fixed flight path angles defined in the behavior model (see Table 15). The ERAM TP does estimate certain vertical trajectory parameters (e.g., top of descent) using backward integration, but the final trajectory is generated using forward integration only.

Table 16: Math models: integration approach

TP	Lateral Integration		Vertical Integration				Integration Type		
	For-ward	Back-ward	Altitude		Longitudinal		Eulerian	2nd Order Runge Kutta	Proprietary
			For-ward	Back-ward	For-ward	Back-ward			
CTAS ER	No	No	Yes	Yes	Yes	Yes		•	
CTAS TA	No	No	No	No	Yes	Yes	•	•	
FACET	Yes	No	Yes	No	Yes	No	•		
GE FMS	No	No	Yes	Yes	Yes	Yes			•
ERAM r1	No	No	Yes	No*	Yes	No	•		

* ERAM uses reverse altitude integration to estimate the TOD location, but then uses forward integration assuming the TOD is at the estimated value to build the actual trajectory (refining the TOD location, if necessary).

As for integration type, the FACET and ERAM TPs use only Eulerian integration, the CTAS Terminal Area TP uses a combination of Eulerian and 2nd Order Runge Kutta (depending on the specific math model), the CTAS En Route TP uses 2nd Order Runge Kutta for all math models, and the GE FMS uses a proprietary approach.

2. Lateral Math Models

Table 17 shows the lateral math models used by the different TPs. The FACET and ERAM TPs use great circle equations for all of their straight (non-turning) behavior models. This is consistent with the fact that both of these TPs use only great circle behavior models (see Table 10 and Table 12). The GE FMS TP uses three types of straight math models: great circle (newer versions are WGS84), constant heading and constant course. This is also consistent with the lateral behavioral models used by this TP (see Table 10, and Table 12). It is interesting that the CTAS TPs only use constant course math models, even though they only have great circle and constant heading^{†††} behavioral models (see Table 10 and Table 12). The CTAS TPs take advantage of the fact that the distances they need to predict over are limited to a single ARTCC airspace and make the mathematical approximation of constant course being equivalent to great circle paths for short distances. For the constant heading segments, the approximation of constant course enables the lateral path to be geometrically approximated rather than integrated (see earlier discussion). An interesting apparent inconsistency is that the GE FMS TP supports constant heading math models, but does not integrate these lateral paths (the lateral path is geometrically approximated, as described earlier). This is possible because the GE FMS TP only uses constant heading segments when it is predicting paths off of the route and its atmospheric model does not use a varying wind field in these cases. This means that the track associated with

^{†††} ERAM’s use of instantaneous turn modeling does not require estimate turn parameters.

^{†††} The Delay Before Capture behavior model is a constant heading straight model.

the constant heading value does not vary over the segment, which enables the GE FMS TP to geometrically determine this path.

Table 17: Lateral Math Models

TP	Straight			Turns		
	Constant Course	Constant Heading	Great Circle	Constant Radius	Variable Bank Angle	Instantaneous
CTAS ER	•			•		
CTAS TA	•			•		
FACET			•		•	
GE FMS	•	•*	•	•		
ERAM r1			•			•

* The GE FMS TP does not have a varying wind field off the aircraft route. Hence, there is no difference between their approach to Constant Heading and Constant Track except for the selection of the initial track value.

For turns, the CTAS TPs and the GE FMS TP use a constant radius turn model for all turns. The turn radius and turn center are approximated using the ground speed from an estimated vertical profile, as discussed previously. The FACET TP uses a variable bank angle model, which includes a model for the “roll in, roll out” behavior to start and end the turn. This is possible because the FACET TP does not require the predicted trajectory to accurately leave one route segment and connect to the next (i.e., its lateral behavior models for straight segments do not include a great circle path between two waypoints). During forward integration of the lateral path, the FACET TP continually checks (using a simplified algorithm) to see if it needs to initiate a turn and when it does, it turns until it can follow a great circle path to the next waypoint, regardless of the original path between route waypoints (the FACET TP is only used for cases where the aircraft is following its flight plan route). The ERAM TP uses instantaneous turn models, so no integration or geometric algorithms are required.

3. Vertical Math Models

Table 18 shows variations of two types of vertical math models used by the TPs: those using equations of motion requiring knowledge of the aircraft thrust and those using equations requiring altitude to be constant. The known thrust models are only used by TPs that use kinetic equations of motion, which rules out the CTAS Terminal Area, FACET, and ERAM TPs. Both the CTAS En Route and GE FMS TPs use known thrust models, including max cruise thrust and idle thrust versions. The GE FMS TP has several additional models beyond those required by the CTAS En Route TP. These are required for the additional vertical behavior models supported by the GE FMS TP (see Table 13, Table 14, and Table 15).

Table 18: Vertical math models: target thrust & constant altitude models

TP	Known Thrust						Constant Altitude	
	Constant Altitude	Constant CAS	Constant Mach	Constant FPA	Constant Vertical Speed	Defined Accel/Decel	Defined Accel/Decel	Constant Speed
CTAS ER	Max Cruise, Idle	Max Climb, Idle	Max Climb, Idle					Mach, CAS
CTAS TA							•	CAS
FACET							•	TAS
GE FMS	Max Cruise, Idle*	Max Climb, Idle, Other**	Max Climb, Idle, Other***	Idle	Max Climb, Idle, Other***	Max Climb, Idle, Other***	•	Mach, CAS
ERAM r1							•	TAS

* GE FMS has the option of using either a constant accel/decel or target thrust.

** Other target thrust values: Derated Max Climb, Takeoff, Derated Takeoff and Max Continuous (Engine Out).

*** Other target thrust values: Derated Max Climb and Max Continuous (Engine Out).

The constant altitude models are used by TPs that use kinematic equations of motion. All of the TPs use some form of a constant altitude, constant speed model (e.g., used to model the constant speed, level flight cruise behavior

models in Table 14). The CTAS Terminal Area, FACET and ERAM TPs do not use kinetic math models (e.g., known thrust and constant altitude) for level flight acceleration/deceleration behavior models, but instead use a defined acceleration/ deceleration rate at constant altitude model.^{§§§} The GE FMS TP has the option to use either kinetic models (known thrust, constant altitude) or kinematic models (constant altitude, defined accel/decel) for these behaviors.

Table 19 shows variations of three additional types of vertical math models used by the TPs: those using equations of motion requiring vertical speed to be constant, flight path angle to be constant, or requiring a defined (not necessarily constant) vertical speed and TAS change rate. The constant vertical speed models are used by the CTAS En Route and GE FMS TPs to cover behavior models explicitly requiring a constant vertical speed (see Table , Table , and Table 1). The GE FMS TP has the option to use a defined accel/decel rate to perform climbing/ descending speed changes using a kinematic model. The constant flight path angle models are similarly used by the CTAS TPs and the GE FMS TP for behavior models (specifically, descent models) explicitly requiring a constant flight path angle (see Table 1). Again, the GE FMS TP has the option to use a defined accel/decel rate to perform climbing/descending speed changes using a kinematic model. The CTAS Terminal Area TP does all of its descending accel/decel segments using this type of model. The defined vertical speed, defined TAS change rate model is used by both the FACET TP and the ERAM TP for all of their climb and descent behavior models (see Table and Table 1). This model uses a vertical speed value and a target TAS value, both retrieved from the aircraft performance model, and both of which vary with altitude.

Table 19: Vertical math models: vertical speed & FPA models

TP	Constant Vertical Speed			Defined Vertical Speed, Defined TAS Change Rate	Constant Flight Path Angle		
	Defined Accel/ Decel	Constant Mach	Constant CAS		Defined Accel/ Decel	Constant Mach	Constant CAS
CTAS ER		•	•			•	•
CTAS TA					•		•
FACET				•			
GE FMS	•	•	•		•	•	•
ERAM r1				•*			

* TAS change rate is a combination of constant accel/decel rate and the rate required to follow ERAM's empirical model's TAS variation with altitude. Observed values for speed and altitude rate can modify the empirical values.

Table 20 shows two polynomial-equation-based math models. These two specialized models are used by the GE FMS TP to model its ground roll acceleration and constant CAS takeoff behavior models (see Table).

Table 20: Vertical math models: polynomial equations

TP	Constant Fuel, Distance, Time	2 nd Order, Fuel, Distance, Time
CTAS ER		
CTAS TA		
FACET		
GE FMS	•*	•**
ERAM r1		

* Used for Ground Roll Accel behavior.

** Used for Constant CAS Takeoff behavior

Table 21 compares some of the TP use of aircraft performance model (APM) data. The CTAS En Route, FACET and ERAM TPs support ground-based systems that deal with a large number of aircraft types, so they contain a range of APM model types, including jet, turboprop, and prop models. The FACET TP uses BADA, a standard

^{§§§} The CTAS TA TP uses a fixed value for the acceleration/deceleration. The ERAM TP uses a value from its performance model. The FACET TP uses a value that will accelerate the aircraft in one integration step.

APM that provides data for 295 aircraft types (99.2% of European air traffic), 103 of the aircraft types are directly modeled and the rest are cross-referenced.⁹ The CTAS En Route and ERAM TPs use their own APM databases and both use cross-referencing between aircraft of similar types to reduce the number of native models required to cover the full range of aircraft types. The CTAS Terminal Area TP does not use aircraft type specific models, so it does not need to have a similar range of aircraft types. The GE FMS TP is installed on a single aircraft, so it only needs modeling data for a single jet aircraft.

The CTAS En Route and GE FMS TPs use math models with kinetic equations of motion (e.g., the known thrust models in Table 18). These math models use thrust and drag data from their APM to support these equations of motion. The FACET and ERAM TPs use vertical rate and TAS schedules from their APM; both sets of data vary with altitude and reflect estimates of complicated pilot procedures. The CTAS Terminal Area, FACET****, ERAM and (optionally) the GE FMS TP all use acceleration/deceleration rates from the APM to model speed changes (see Table 18 and Table 19). The CTAS En Route, FACET, and GE FMS TP all use fuel flow data from their APM to determine fuel burned over the length of the trajectory.

Table 21: Math models: aircraft performance model

TP	Model Types	Cross-Reference Types	Drag Data	Thrust Data	Altitude Rate	TAS Schedule	Accel/Decel Rate	Fuel Flow
CTAS ER	J, T, P	•	•*	•*				•*
CTAS TA							•	
FACET	J, T, P	•			Climb, Descent	•	Max Only	•**
GE FMS	J		•***	•***			•	•***
ERAM r1	J, T, P	•			Climb, Descent****	•	•	

J = Jet, T = Turboprop, P = Prop

* CTAS drag data includes clean, flaps, gear, and speed brakes; Thrust data includes Idle, Max Climb, Max Cruise, and Corrected; Fuel Flow includes Idle, Max Climb, and Corrected.

** FACET Fuel Flow includes Corrected.

*** GE FMS has extensive Drag data for the aircraft in which it is installed; Thrust and Fuel Flow data includes Idle, Max Climb, Derated Max Climb, Takeoff, Derated Takeoff, Max Continuous (Engine Out), and Corrected

**** ERAM empirical altitude rates (and speeds) can be modified by observed data (Aircraft Trajectory only).

E. Output Trajectory Data

The output trajectory is the final result of the TP. The data included in the final trajectory, as well as the format are typically, at least to some degree, dictated by the client application that uses the trajectory. In all of the tables below, the computed (internal) trajectory was used for the FACET TP since it does not actually output a trajectory to FACET.

Table 22 shows the lateral trajectory data returned by the TPs. The GE FMS TP does not return lateral data at each predicted point of the trajectory. Instead, it returns a series of straight lines and arcs. This data is used by the FMS to perform lateral guidance when in the Lateral Navigation (LNAV) flight mode. This data can be correlated to the vertical data to provide along path distance and true course, but it is not done explicitly in the output trajectory. The CTAS TPs, FACET and ERAM TP all provide position data (either in X/Y or Lat/Lon) and some combination of course and/or heading data. All but the FACET TP also provide along path distance at each predicted point. The CTAS TPs and the GE FMS TP also provide explicit turn geometry data for each turn waypoint, including the turn radius and turn center position.

**** FACET uses a maximum acceleration/deceleration rate from its performance model to limit its speed changes, which it attempts to perform in one integration step.

Table 22: Trajectory data: lateral

TP	Separated Data		Data at Each Predicted Point					Turn Data		
	Straight Lines	Arcs	X/Y	Lat/Lon	Along Path Distance	True Course	Heading	Turn Way-point	Turn Radius	Turn Center
CTAS ER			•		•	•	Magnetic	•	•	•
CTAS TA			•		•	•	Magnetic	•	•	•
FACET				•			True			
GE FMS	•	•			o	o		•	•	•
ERAM r1				•*	•	•				

* ERAM converts output to geodetic latitude and longitude

Table 23 shows the time, altitude and speed data provided by each TP at each predicted point. All of the TPs provide time, predicted altitude, and true airspeed data. The GE FMS TP also returns a reference altitude at each point. This altitude relates to a stored trajectory that the vertical guidance is currently using and gives an indication of predicted vertical deviation from this reference path. The CTAS TPs and the GE FMS TP also return Mach (not for CTAS Terminal Area TP) and CAS at each point and the CTAS TPs, FACET and ERAM also return ground speed. All of the TPs except the GE FMS return vertical speed and the CTAS En Route, and GE FMS TP return flight path angle data.

Table 23: Trajectory data: time, altitude, and speed

TP	Time	Altitude		Speeds				Vertical Speed	FPA
		Predicted	Reference	Mach	CAS	TAS	Ground		
CTAS ER	•	•		•	•	•	•	•	•
CTAS TA	•	•			•	•	•	•	
FACET	•	•				•	•	•	
GE FMS	•	•	•*	•	•	•			•
ERAM r1	•	•				•	•	•	

* GE FMS maintains a reference theoretical descent profile. This data is returned with each trajectory for guidance purposes.

IV. Interoperability Impacts

Differences in TP capabilities of disparate TPs create requirements for successful integration when sharing trajectory data. The following example illustrates the issues. This text was taken from a final deliverable document. It will be rewritten in a form more appropriate for a conference paper.

For this scenario, it is assumed that the suppliers of trajectory data are aircraft equipped with a conventional Flight Management System (FMS) being used for Navigation/Guidance. The GE FMS is assumed to be the FMS onboard all aircraft. For LNAV/VNAV guidance modes, the GE FMS is assumed to be the provider of behavior model data. For all other guidance modes, the behavior models are based on extensions of the GE FMS behavior modeling. For this scenario, the receiver of trajectory data is a ground-based separation management system. This system is supporting a controller with automated conflict detection (CD) and conflict resolution (CR) capabilities. There are two options for the ground-based system performing separation management: En Route Descent Advisor (EDA) and En Route Automation Modernization (ERAM).

In Figure 1, aircraft A is an arrival aircraft descending in LNAV/VNAV guidance to an arrival fix at the TRACON boundary (the figure is a vertical view of the two aircraft). The aircraft's descent profile is created within the aircraft's FMS to meet an altitude and speed restriction at this fix. The arrival fix and its altitude and speed constraints are also known by the ground systems as part of the aircraft's flight plan. Aircraft B (crossing traffic) is flying level in LNAV/VNAV. Laterally, both aircraft are flying their routes as defined in their flight plans.

A loss of separation between aircraft A and B will occur along aircraft A's descent trajectory. If no data are shared between the ground and air systems, the conflict might not be detected (a missed alert) and/or an incorrect

conflict might be detected (a false alarm). Data sharing should provide enhancement to the ground knowledge of the descent trajectory improving prediction accuracy and therefore reducing the chances of a false alarm or missed alert.

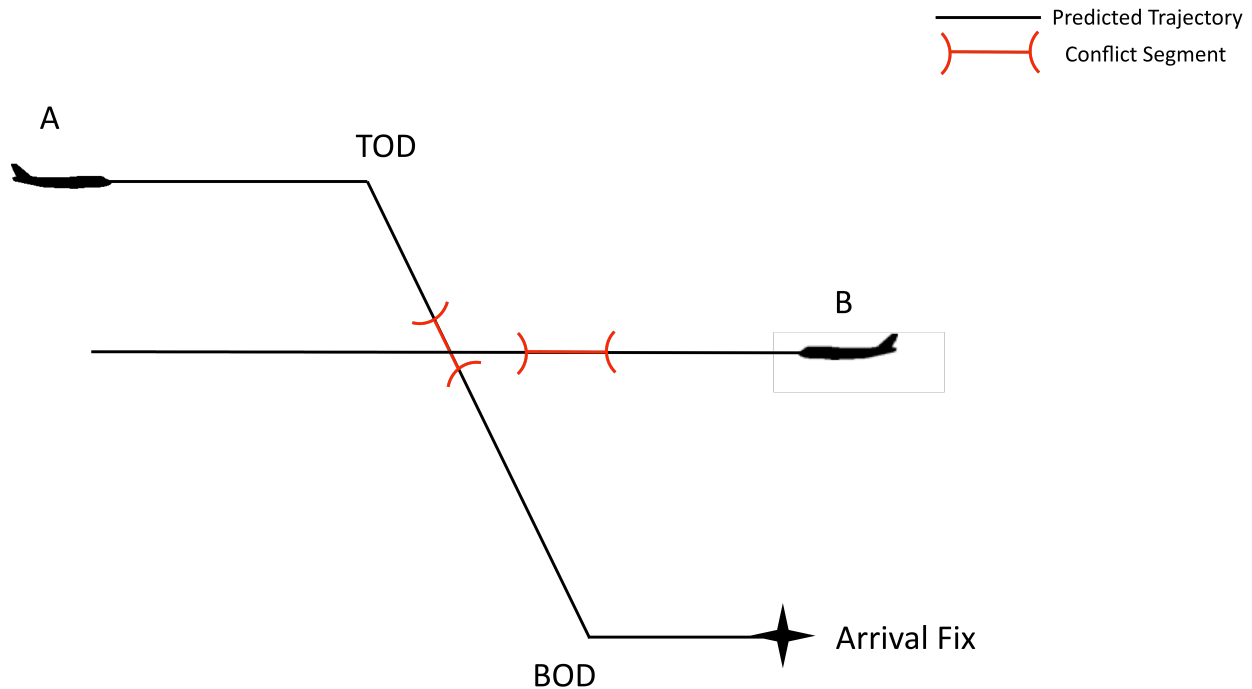


Figure 1: Descending aircraft scenario.

A. Intent Data Sharing

One option to improve the predictability on the ground would be to downlink additional intent information from the aircraft. For this scenario, it would be sufficient for the aircraft to downlink the following information to represent its lateral and vertical intent:

- current FMS route lateral waypoints including any associated altitude/speed constraints
- cruise altitude
- current commanded speed profile
 - cruise Mach
 - descent speed profile (Mach and IAS)
- TOD location

The information available to the ground systems that are not contained in the flight plan would then be the descent speed profile (Mach and IAS) and the TOD location. In the case of an aircraft supplier of trajectory data, the FMS predicted TOD location can be considered part of the intent information because it is an input to the aircraft's guidance system (it is used to define the initiation point of the descent). A benefit of sharing TOD location information would materialize only if the ground systems are able to use this information. Currently, neither ERAM nor EDA can introduce this information into their TP process. The use of downlinked TOD data is not required for this approach to achieve benefits.

For EDA, the knowledge of the aircraft's current descent speed profile will improve the accuracy of the EDA TP to better determine whether the aircraft needs to be delayed to meet its scheduled time of arrival and to better detect conflicts prior to issuing a meet-time or conflict resolution advisory. If EDA is creating resolution or meet-time advisories that do not include changing the aircraft's descent speed profile, knowing the aircraft's current descent speed profile would also improve the effectiveness of the generated advisories. If EDA generates a descent speed

profile advisory, however, EDA would typically retain knowledge of these clearances, so from then on the downlinked descent speed profile data would be less beneficial.^{††††}

For ERAM, there does not appear to be any benefit to sharing this intent data. The reason is that ERAM does not accept descent speed profile constraints as inputs. ERAM uses an empirically defined model of true airspeed (TAS) variation with altitude for its descent trajectory generation. This is consistent with the environment for which ERAM was developed (where no data sharing is available), but it does not allow ERAM to take advantage of the additional shared intent data. Without rewriting the way ERAM handles descent speeds, it does not appear possible to use Intent Data sharing to synchronize ERAM trajectories for this scenario.

B. Behavior Model Data Sharing

In this scenario, the aircraft are responsible for generating behavior models and downlinking them to the ground-based systems. For a description of behavior model sharing as a form of achieving interoperability, see reference 7. For the GE FMS, the behavior model for aircraft A descending to the arrival fix in LNAV/VNAV are presented in Table 11 and Table 13.

Table 11: Scenario 2 Aircraft A generated lateral behavior model.

Maneuver Sequence Number	Behavior Model Name	Description	Data Required
1	Route-Following: Straight: Great Circle: To a WP	From initial condition to the arrival fix	Arrival fix position and inbound course

This lateral behavior model assumes that aircraft A is flying on a great circle path to the arrival fix, which is in front of the aircraft.

Table 13: Scenario 2 Aircraft A generated vertical behavior model.

Maneuver Sequence Number	Behavior Model Name	Description	Data Required
1	Cruise: Level: Constant Speed: Mach	Cruise at constant altitude and Mach until reaching the TOD	Cruise Mach, cruise altitude, descent Mach, descent CAS, arrival fix altitude, arrival fix position, arrival fix CAS constraint
2	Descent: Descending: Constant Speed: Mach: Idle Thrust	Descend at constant Mach from TOD until capture Mach/CAS transition	
3	Descent: Descending: Constant Speed: CAS: Idle Thrust	Descent at constant CAS from Mach/CAS transition to arrival fix altitude (BOD)	
4	Descent: Level: Capture speed	Decelerate from descent CAS to arrival fix CAS	

Either the TOD location (if included as intent) or the definition that the TOD is predicted such that the last maneuver (#4) ends at the arrival fix location must be provided.

For aircraft B in the cruise phase of flight for LNAV/VNAV:

Table 15: Scenario 2 Aircraft B generated lateral behavior model.

Maneuver Sequence Number	Behavior Model Name	Description	Data Required
1	Route-Following: Straight: Great Circle: To a WP	From initial condition to the route waypoint B1	Waypoint B1 location

This lateral behavior model assumes that aircraft B is flying on a great circle path to a single waypoint (B1) in front of the aircraft.

^{††††} This does not address the potential architectural benefits of having the aircraft broadcast the data, removing the need for EDA to track this data internally.

Table 16: Scenario 2 Aircraft B generated vertical behavior model.

Maneuver Sequence Number	Behavior Model Name	Description	Data Required
1	Cruise: Level: Constant Speed: Mach	At cruise altitude and current commanded Mach	Cruise Mach and Cruise Altitude

For the receiving systems the behavior model from Table 11 through Table 16 need to be translated to a form that is usable by those systems. The converted behavior models for aircraft A and B for the two ground systems are presented in Table 17 through Table 20.

Table 17: Scenario 2 GE FMS lateral behavior (Aircraft A & B) models converted to ERAM and EDA lateral behavior models.

Maneuver Sequence Number	GE FMS Behavior Model Name	ERAM Behavior Model Name	EDA Behavior Model Name
1	Route-Following: Straight: Great Circle: To a WP	Route Capturing: Waypoint Capture: Delay Before Capture	Route Capturing: Waypoint Capture: Delay Before Capture
		Route-Following: Turns: Waypoint Capture: Turn to Capture Waypoint	Route-Following: Turns: Waypoint Capture: Turn to Capture Waypoint
		Route Capturing: Waypoint Capture: Great Circle to WP	Route Capturing: Waypoint Capture: Great Circle to WP

This is the closest approximation of the lateral behavior model between the FMS, ERAM and EDA.

Table 11: Scenario 2 GE FMS (Aircraft A) Vertical behavior model converted to ERAM and EDA vertical behavior models.

Maneuver Sequence Number	GE FMS Behavior Model Name	ERAM Behavior Model Name	EDA Behavior Model Name
1	Cruise: Level: Constant Speed: Mach	Cruise: Level: Constant Speed: mach	Cruise: Level: Constant Speed: Mach
2	Descent: Descending: Constant Speed: Mach: Idle Thrust	Descent: Descending: Descent	Descent: Descending: Constant Speed: Mach: Idle thrust
3	Descent: Descending: Constant Speed: CAS: Idle Thrust		Descent: Descending: Constant Speed: CAS: Idle thrust
4	Descent: Level: Capture speed	Descent: Level: Capture Speed: TAS	Descent: Level: Capture Speed

Table 20: Scenario 2 GE FMS (Aircraft B) Vertical behavior models converted to ERAM and EDA vertical behavior models.

Maneuver Sequence Number	GE FMS Behavior Model Name	ERAM Behavior Model Name	EDA Behavior Model Name
1	Cruise: Level: Constant Speed: Mach	Cruise: Level: Constant Speed: Mach	Cruise: Level: Constant Speed: Mach

For aircraft B, all three systems use the same behavior model, so no conversion is required. The rest of the discussion focuses on aircraft A.

For EDA, the entire descent behavior model matches the GE FMS behavior model (Table 11), so no conversion is required. This is expected since EDA's trajectory generation was built to be "FMS-quality" and has its origins

from the same basic math modeling. For conflict probing, since EDA's behavior modeling in this case matches the GE FMS behavior modeling, there is actually no improvement over intent data sharing. In cases where EDA's modeling was unable to identify accurately the behavior model just from the intent information, this approach would provide better accuracy for the EDA conflict probe. For conflict resolution, the intent data sharing approach is expected to be more desirable because the descent speed profile is clearly identified as a constraint and can be reused, as necessary in candidate resolution trajectory generation.^{****}

For ERAM, the cruise maneuver before TOD is the same as that for the GE FMS, so no conversion is required. During the descent, ERAM uses a much simpler behavior model (Descent: Descending: Descent) than either the GE FMS or EDA. This reflects ERAM's design decision to add its trajectory generation complexity to its empirical math modeling as opposed to its behavior modeling.^{****} The final ERAM level maneuver is similar to that for the GE FMS except that for ERAM the speed to capture is defined in TAS instead of CAS. The arrival fix speed constraint sent with the GE FMS behavior model would have to be converted by ERAM.

As discussed in the intent data sharing approach, ERAM does not accept descent speed profile constraints as inputs. This causes the same negative impact to the behavior model sharing approach, namely, without rewriting the way ERAM handles descent speeds, it does not appear possible to use behavior model sharing to synchronize ERAM trajectories for this scenario.

C. 4D Trajectory Data Sharing

For this scenario, the 4D trajectory predicted by the GE FMS would be downlinked to the ground systems. This would be represented by a series of predicted future 4D states that include, at a minimum, position (latitude and longitude), altitude and time.

For EDA, downlinking a 4D trajectory may improve the performance of its conflict probe since the FMS predicted TOD is a part of the downlinked trajectory. That being said, it is not expected that this approach will provide a significant improvement over the other two data approaches in terms of conflict detection since both intent data and behavior model sharing work very well in improving EDA's prediction accuracy for this scenario. This approach would only be significantly more effective than the other two if the aircraft's math modeling were significantly better than EDA's. Due to the aircraft's atmospheric modeling deficiencies, the aircraft trajectory could actually be less accurate than one generated by EDA. For conflict resolution, downlinking a 4D trajectory doesn't provide any support for generating resolutions and is therefore the weakest of the three approaches.

For ERAM, downlinking a 4D trajectory is the first data sharing approach that enables an improvement to the ERAM conflict probe. This is because the impact of the descent speed profile is included in the downlinked 4D trajectory, which is an intent error source for ERAM generated trajectories. For conflict resolution, downlinking a 4D trajectory still doesn't provide any support for generating "what-if" solutions on the ground. This approach to data exchange is therefore no worse for ERAM than the other three approaches for conflict resolution purposes.

V. Conclusion

The aircraft trajectory prediction capabilities of five state-of-the-art trajectory predictors were captured and compared to illustrate the commonality and differences between current-day trajectory prediction technologies. The approach taken and detailed results for the comparisons of the input state data, constraints handled, behavior and math models used, input atmospheric models, and output trajectory data are presented. The comparisons illustrate how design approaches chosen by each TP to meet the objectives of its client application create significant differences between the capabilities of the different TPs.

A scenario was presented to illustrate the issues that arise when attempting to achieve interoperability between air traffic management automation through trajectory information sharing. An air-ground scenario was chosen where airborne flight management systems downlink trajectory information to support two options (ERAM and EDA) for a ground-based system providing controller conflict detection and resolution support. Three forms of trajectory data sharing (intent, behavior model, 4D trajectory) were analyzed to show the strengths and weaknesses of each approach in achieving interoperability. Due to the similarities in capabilities between the GE FMS TP and the EDA TP, interoperability is more achievable between these systems than between the GE FMS and ERAM systems. The scenario illustrates how different design approaches chosen by different TPs to meet the needs of their specific

^{****} Though the descent speed profile is available from the behavior model, it is most likely not going to be stated explicitly as a constraint. This adds at least a minimal chance for incorrectly inferring these speed constraints from the behavior model data (though arguably a negligible chance in this specific scenario).

^{****} For more discussion on this topic, see reference 8.

environments, specifically the ERAM use of simplified behavior models and empirical math models to deal with the lack of known aircraft speeds, can cause significant impediments to achieving system interoperability.

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